Full Scale Evaluation of Lightweight Personal Protective Ensembles for Demining

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1. Introduction

A wide range of equipment, in the form of helmets, vests, aprons, trousers, etc., is currently in use around the world to protect deminers against the effects of anti-personnel (AP) mines. Significant variations exist in terms of the level of protection afforded, operational usefulness, quality of manufacture and cost of each of these components. To date, there had been only limited studies undertaken to systematically and quantitatively assess the effectiveness of the different protective components finding their way to both the civilian and military demining theatres. This study summarizes the efforts of numerous full scale test series carried out during 1999, with particular emphasis on quantifying the protective performance against blast AP mines of selected concepts of humanitarian demining ensembles. Concurrently, it was possible to also assess aspects of the blast and related fragmentation resistance of individual components.

To this effect, full size human surrogates have been used, in the form of instrumented anthropomorphic mannequins. In order to provide meaningful and reproducible data, in the context of explosive blast experiments, it was necessary to devise a "blast resistant" test set-up which permitted realistic experiments to be conducted. There had been no systematic studies conducted to date involving instrumented human surrogates exposed to a wide range of blast AP mine threats, and the relative protection afforded by different demining protective kit had not been quantitatively evaluated. For this purpose, advanced positioning rigs were developed and constructed by Med-Eng Systems (MES), which permitted the mannequins to be accurately and reproducibly supported in various common positions used by deminers. The mannequin, dressed in a particular protective ensemble and configured in the desired position, was suspended at representative field operating distances from a (simulated or actual) mine, as deduced from measurements taken with deminers.

The HDE Demining Ensembles (by MES) were extensively tested, along with a range of different helmets and customized full-faced visors under development, including some based on the military PASGT-style, hardhats and sporting helmets. To simulate equipment sometimes deployed by militaries involved in demining, a standard issue flak vest, ballistic chaps, and a PASGT-style helmet worn with safety goggles, were also tested. At the same time, different hand protector concepts under development were similarly worn on the mannequin and subjected to representative blast conditions. Pressure sensors and accelerometers mounted on the chest and head of the mannequins were used to evaluate the protective performance of the equipment.

2. Experimental Details

In order to perform the experiments for this study, instrumented Hybrid II mannequins were used, representing the 50th percentile North American male (height: 1.75 m, mass: 77kg). Such test surrogates were commonly used in the automotive industry for injury assessment of the occupants

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during crash tests. The joints of the mannequins were tuned prior to each experiment for a relatively realistic initial response when subjected to the blast loading.

2.1 Mannequin Positioning Apparatus & Instrumentation

One of the key aspects of testing with mannequins is that in order to obtain repeatable and systematic data, the mannequins must be positioned consistently and realistically. In order to attain this objective an advanced positioning apparatus was designed and constructed. The apparatus consists of a large base structure with two supporting arms, which can be set at a range of angles from near-horizontal to vertical. The arms are far enough apart that a mannequin easily fits between them. On these arms, by means of adjustable brackets, sit two cross-bars which connect (by means of chain links) to the mannequin's hips and shoulders. The cross-bars are not rigidly attached to the supporting arms but are held in place by the mannequin's weight. Every component on the apparatus can be adjusted by discrete amounts in order that positions can easily and accurately be recreated. The use of small link chains and the movable cross-bars allow the mannequins to move freely during the initial blast event, thereby preserving the initial bio-fidelity of the mannequin's response.

The versatility of the test apparatus allows the mannequins to be placed consistently in a wide variety of typical demining positions, including kneeling-on-one or two knees, standing, squatting, and crouching. Figure 1 illustrates a mannequin placed in a crouching position (prior to a blast), similar to a technician inspecting or excavating a mine . In most tests performed, two mannequins were utilized in order to obtain two sets of data for each mine blast. Figure 2a shows a typical set up where the mannequins were supported in a kneeling-on-one-knee position, prior to a mine detonation, via means of two separate positioning rigs. For the evaluation of equipment and injury potential performed for this study, the mannequins were all placed in a kneeling-on-one-knee position with their sternums 0.66 to 0.68 m from the simulated mine, which represented the typical distance a deminer's sternum would be from a mine while prodding with a prodder of approximate length 40 cm (+/- 10 cm).

In order to quantify the performance of the various protective equipment evaluated, each mannequin was instrumented with separate clusters of tri-axial (PCB) accelerometers in the head and chest, along with two separate (PCB) pressure transducers for measuring overpressure at the ear and at the sternum. All instrumentation lines were connected via appropriate power supplies and signal conditioning equipment to a computerized data acquisition system. The sensors were calibrated prior to each test series.

2.2 Mine Threats

Since actual AP mines are not readily available, simulated mines were extensively used. These consisted of C4 plastic explosive packed snugly into injection molded puck-shaped plastic containers, and buried with 1 cm of overburden in front of the mannequins. Three sizes of simulated mines were used containing 50, 100 and 200 grams of C4, chosen to represent a wide range of blast type AP mines. Actual AP mines were selectively utilized for assessing the overall blast and fragmentation resistance of the protective components.

Figure 1. Mannequin placed in crouching position, illustrating versatility of mannequin positioning apparatus

Figure 2. Mannequins kneeling on one knee, dressed in HDE with Sport helmets and positioned 0.66 m between sternum and simulated blast AP mine (200 gram C4); a) pre-blast (left), b) post blast (right)

3. General Observations on Blast Integrity of Components

The HDE Demining Ensemble is comprised of two components, a frontal upper body and groin protection apron and frontal leg protection trousers, designed to overlap and provide continuous frontal protection from the neck to the bottom of the shin. The Basic HDE is constructed of soft and hard ballistic materials, in combination with a blast attenuation system over the vital regions of the chest and groin, to provide protection from fragmentation, blast overpressure and impact. The Enhanced HDE uses an extra layer of high density rigid ballistic material overtop the Basic layout. Under blast testing, against a range of simulated and actual blast type AP mines, i.e., PMA1, PMA2, PMA3, PMN, the blast integrity of the HDE was adequate in preventing any fragmentation penetration or apparent blast damage from reaching the body. The entire ensemble remained in place over the mannequin for all tests conducted under an extensive range of blast severities. The military flack vest and chaps were only tested with simulated mines and similarly remained in place, unpenetrated, over the mannequins for a much smaller number of tests.

Several helmet concepts have been designed, all of which employed the helmet as a platform for mounting a full-face fragmentation resistant visor. Three styles of helmets were developed, i.e., the “HDH1 & HDH2”, which utilize a military PASGT-style helmet with an advanced retention system (one of which is visible in Fig. 1); the “Sport1 and Sport2” helmets which use a lightweight sporting helmet (visible in Fig. 2); and the “Hardhat1 and Hardhat2” helmets based on a construction hardhat, a solution commonly deployed in demining theatres. Two different versions of each style were developed, each employing slightly different concepts in construction and design, in order to evaluate a larger number of possible solutions for providing head and facial protection. A commercial PASGT-style helmet with ballistic goggles was also tested.

From a blast integrity perspective, the HDH and Sport helmets have shown themselves to perform best, as they consistently remained in place over the mannequins' heads and were only once penetrated at the visor (6.32 mm,1/4"). The Hardhat helmets, on the other hand have proven to be alarmingly weak and susceptible to failure, even at low blast strength. Due to this, it is feared that similar hardhat based solutions currently in use in demining theatres around the world may be providing inadequate protection for at least the upper range of AP mine threats (>100 g TNT) that can be encountered. Alarmingly, the PASGT-style helmet with goggles (no visor) were both ejected by the blast from the mannequin's head for mines containing as little as 100 grams C4.

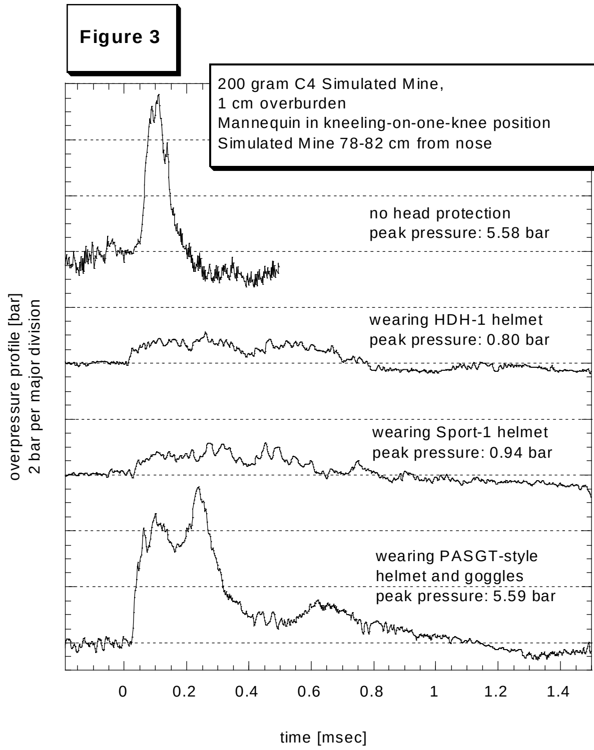
Several hand protection concepts have also been developed by MES, constructed of rigid and soft ballistic materials assembled in aerodynamic shapes, which can be used in various roles in a demining setting (i.e., prodding, detecting, etc.). They have consistently (over 150 tests) proven themselves capable of stopping fragmentation from the full range of mines tested at close range (as close as 16 cm). It seems promising that these systems may be able to save a deminer's hand in the case of an accident, however this needs to be verified through testing involving biological specimens.

Fig. 2b shows the post blast scene after two mannequins, dressed with the HDE, Sport helmets, hand protectors and detachable sleeves, were exposed to a simulated mine containing 200 gram C4 . The overall integrity of the equipment against the threat is clearly visible. For further discussion on the construction and blast integrity of the HDE and the components developed, please see [1].

4. Results and Discussion

4.1 Assessment of Overpressure Injury at the Ear for Different Helmet Systems

The ear is most susceptible to blast overpressure injury, compared to other regions of the body. The threshold of eardrum perforation lies at a mere 0.35 bar. An overpressure of 1 bar will yield 50 % probability of eardrum perforation, while a 95 % probability of eardrum perforation is predictable for an overpressure of 2 bar. Damage to the inner ear, which will invariably result in some degree of permanent and irreversible loss of hearing, generally occurs for overpressures above 1 bar. Although eardrum perforation, or loss of hearing, are not life-threatening injuries, they can be a life-long handicap with potentially detrimental social consequences. It is thus important, to sufficiently attenuate the blast overpressure level at the ears and to assess the pertinent shielding capabilities of the various helmet systems tested over the full range of blast AP mine threats.



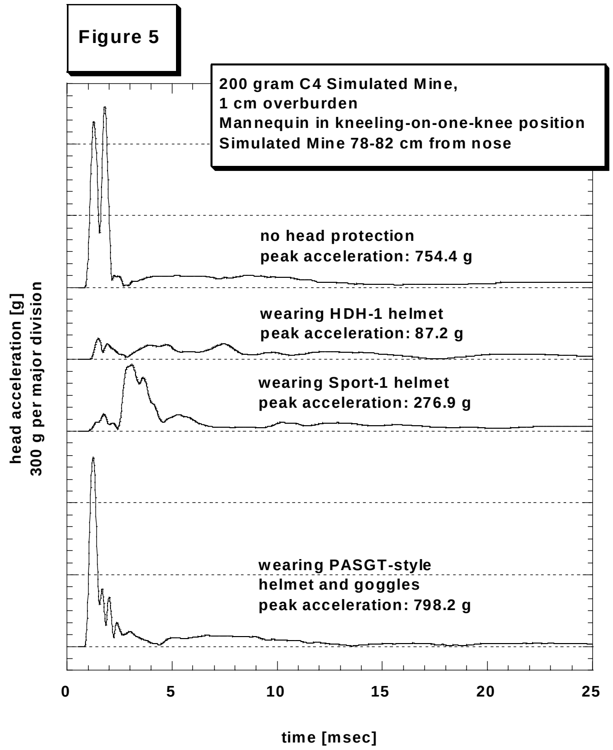


Figure 3. Typical traces of overpressure measured at ear of mannequin from detonation of simulated AP mine.
Figure 5. Typical traces of resultant acceleration, as measured at the centre of gravity of mannequin's head exposed to blast from simulated AP mine (200 gram C4).

Figure 3 presents the typical pressure traces measured at the ear of the mannequins, when exposed frontally to a blast from a simulated AP mine (200 gram C4), and wearing different head protection concepts. The trace obtained for the unprotected mannequin features a sharp rise in pressure generated by the passing blast wave, followed by a smooth decay. When the mannequin is dressed with a helmet that is securely mounted on the head and features a well-integrated full face visor, such as the HDH-1 and Sport-1 helmets, the pressure signal is greatly attenuated in amplitude (< 1 bar) and rate at which the pressure rises. However, if goggles and an open-faced PASGT-style helmet are worn, the peak pressure measured at the ear is comparable to that of wearing no protection (i.e., 5.6 bar) and is drastically higher than that measured for the HDH-1 and Sport-1 helmets at the same blast conditions. It is proposed that the flared out ear-cups of the PASGT-style helmet design serves to trap the blast overpressure, in the absence of a full-face visor, and is observed to actually prolong the duration of the pressure pulse considerably (1.0 ms) compared to the unprotected head (0.15 ms).

Fig. 4 gives the average value of the peak overpressure measured at the ear of the mannequins for the three charge sizes (50, 100, 200 gram C4), and for different helmet options mounted on the mannequins. It can be seen that the HDH helmets are consistently the best performers over the range of charge sizes, followed by the Sport helmets. The performance of the Hardhat helmets is considerably worse overall. It can be seen that the use of the PASGT-style helmet without a full face visor results in a higher overpressure than wearing no protection, for the full range of AP mine blast conditions tested.

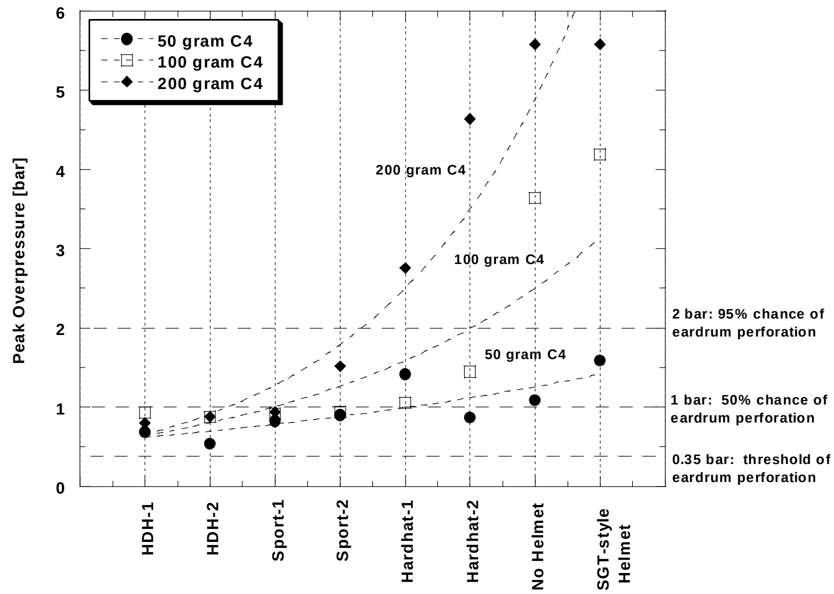


Figure 4. Average peak overpressure measured at ear of mannequins in kneeling-on-one-knee position, facing simulated mines of 50, 100, and 200 gram C4, buried with 1 cm overburden, 0.66-0.68 m from sternum.

The known thresholds of overpressure for ear injury have been superimposed on Fig. 4. For the particular position of the mannequin and distance from the mine, it appears that all helmets tested permitted the overpressure to the ear to rise above the threshold for ear drum perforation, i.e., 0.35 bar, even for the smallest charge of 50 gram C4. The overpressure transmitted to the ear when the HDH and Sport helmets were worn did not exceed the 50% probability threshold for ear drum perforation, i.e., 1 bar, for all AP mine blast conditions tested. From the full-faced visors, Hardhats did not perform nearly as well, particularly at the 200 gram C4 condition, where measured ear pressures were well in excess of 2 bar, i.e., 95% probability of ear drum perforation. For the unprotected deminer, not wearing any protection, or for the deminer wearing a helmet without a face shield (i.e., the PASGT-style helmet/goggles), the overpressures experienced are well above the threshold for a 95% chance of eardrum perforation (when facing 100 and 200 gram of C4) and would likely result in inner ear damage coupled with some form of permanent hearing loss. Although the actual structure of the human ear is not identical to that of a mannequin, the injury levels estimated for the different helmets could still be used as a reasonable guideline.

4.2 Head Acceleration Injury Assessment for Different Helmet Systems

When the head of a victim is subjected to a sudden and violent loading, such as that produced by the blast wave generated from a detonating mine (or other explosive device), a range of injuries can result ranging from minor to unsurvivable. The head region is particularly susceptible to this blast induced head acceleration. Figure 5 presents typical resultant head acceleration traces experienced by the mannequin's head, wearing different helmets and exposed to the blast from a 200 gram C4 simulated mine. For the "Unprotected" case, a sharp jump in the acceleration experienced is observed, i.e., 754 g's. This value can be greatly reduced when appropriate protective gear is worn, as evidenced from the traces of the mannequin wearing an HDH-1 (87 g's) and Sport-1 helmet (227 g's). Several contributing factors are attributed to this significant reduction in the head acceleration, including the presence of a full faced visor to aerodynamically

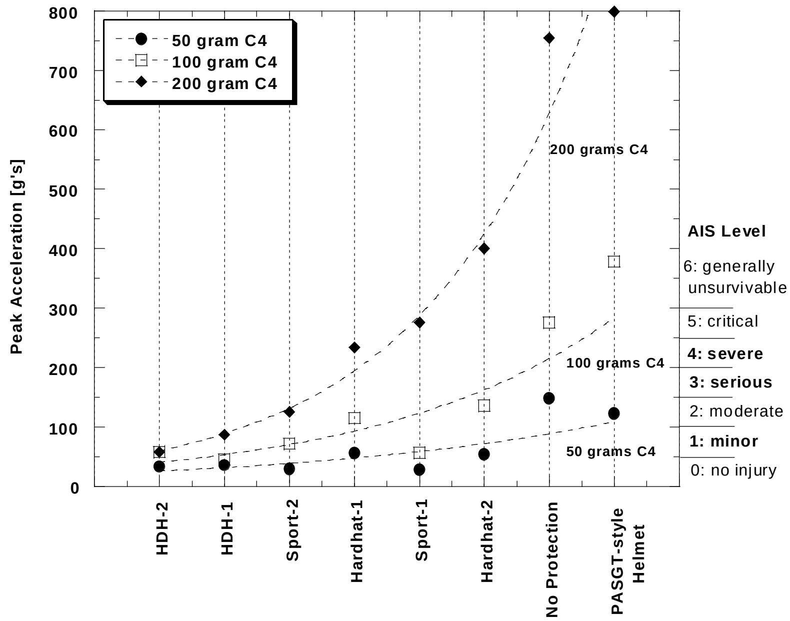


Figure 6. Average peak resultant acceleration, measured at centre of gravity of mannequin's head, and AIS head concussion injury scale. Mannequins in kneeling-on-one-knee position, facing simulated mines of 50, 100, and 200 gram C4, buried with 1 cm overburden, 0.66-0.68 m from sternum.

deflect the blast wave, a suitable retention system, deflection and energy absorption of the helmet components, an interlocking visor with the top of the chest plate of the HDE, etc. Similar to the results pertaining to ear overpressure, wearing a PASGT-style helmet with no visor results in worse head accelerations than for the case of the mannequin wearing no protection. The flared out ear-cups of this design create a larger profile for the blast to interact, and furthermore, trap the blast, resulting in a higher head acceleration.

In comparing the average peak head acceleration measured among the different helmet options, and across the range of AP mine threat sizes, as presented in Fig. 6, it is apparent that the HDH helmets are the better performing helmet options, followed by the Sport helmets (permitting for some scatter in the data). The Hardhats, as a group, perform the poorest in reducing the acceleration from the full-faced visor options tested. Facing 100 and 200 grams of C4, it is apparent that wearing a helmet with no visor is worse than wearing nothing at all, from the perspective of frontal blast-induced head acceleration. Figure 6 illustrates that as the explosive threat in the AP mine is increased, the resultant head acceleration experienced also increased for all helmet configurations.

In order to determine the potential for closed head injuries from blast induced acceleration, the 1985 Abbreviated Injury Scale (AIS), which assigns the severity of concussive head injury, has been correlated with peak head acceleration values [2,3]. Severity of head injury increases with an increase in the peak acceleration experienced by the head, ranging from no injury, to dizziness, to different levels of unconsciousness, and ultimately to death. In this relatively simplistic approach, the injury severity is linked to discrete ranges of peak g's in increments of 50. In reality however, the severity of injury does not actually depend on such discrete steps, as there exists a spectrum of injury probabilities that are possible at each condition, depending on numerous factors, including an individual's physical condition, health, age, orientation, etc. Despite its shortcomings, the AIS scale is a good first approximation in assessing the injury potential that can result and has been plotted on the right vertical axis of Fig.6, alongside the data for the peak head acceleration experienced.

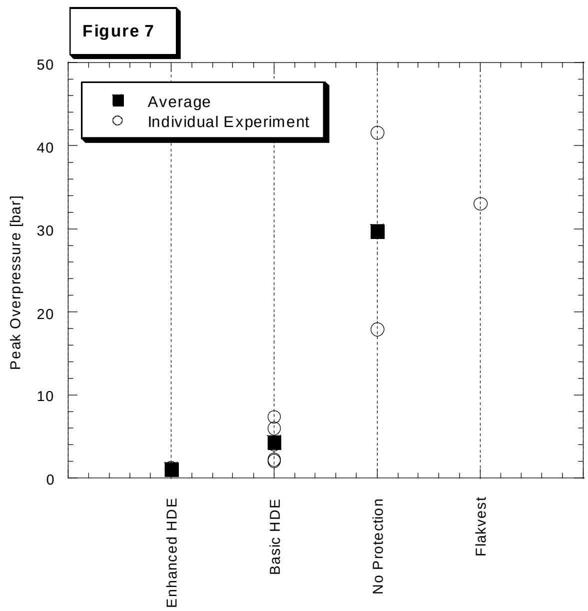
For all head configurations considered, it is clearly observed that the severity of head injury increases with an increase in the explosive content of the AP mine. For a mine containing 50 gram C4, it appears that wearing any of the tested helmets that incorporate a full-face visor, i.e., HDH, Sport and Hardhat, limited the head injury to at most a minor level, i.e., headache/dizziness. The unprotected deminer, or one wearing a PASGT-style helmet with goggles and no visor, would not be expected to receive beyond a moderate head injury, i.e., brief unconsciousness. As a reminder, the statements presented here only hold true for the test conditions used in these tests. Injury potential can differ greatly with a reduction or increase in the separation distance of the deminer from the mine.

The benefit in wearing a full face visor on a securely mounted helmet is demonstrated for the larger mine containing 100 gram C4, where again only a minor injury would be expected when the HDH and Sport helmets were worn. The Hardhats seem to escalate the head injury to one level higher, i.e., moderate, while wearing no facial protection, or the PASGT-style helmet without a visor, may lead to critical or unsurvivable injuries. At 200 gram C4, the injury potential increases significantly, as the accelerations experienced also increase substantially. Based on just a few tests, only the HDH helmets seem to limit the injury level to the minor regime. The Sport helmets keep the injury level to within survivable levels, but the Hardhat helmets straddle the generally unsurvivable threshold. If no head protection is worn, or the PASGT-style helmet without a face shield is worn, there is a high probability of a fatal head concussion resulting, since the resultant acceleration levels experienced are well above the 300 g’s threshold. This, once again, points to the clear benefit and necessity for a deminer to wear a full-face visor mounted on a stable helmet platform. The data presented above should be treated as a guideline for relative injury assessment based on the different threat conditions and protective equipment utilized. The correlation of head injury with blast induced head acceleration has not yet been validated using instrumented biological surrogates.

4.3 Attenuation of Blast Loading (Overpressure and Acceleration) to the Thoracic Cavity

The effectiveness of the flakvest and HDE’s in attenuating the thoracic blast loading was investigated through measurements of the transmitted overpressure at the chest wall and gross chest acceleration of the Hybrid II mannequin. Although the different ensembles were tested over the full range of simulated blast AP mines (50-200 gram C4), only the results for the largest of the threats will be presented here. The data for the smaller mines exhibited essentially the same relative trend in attenuation capability by the test candidates, except for the smaller peak values of the signals.

Figure 7 illustrates the peak overpressures measured at the sternum of the mannequins (kneeling on one knee with sternum 66-68 cm from the mine) when facing the simulated mine, containing 200 gram C4. It is immediately apparent that the Enhanced and Basic HDE’s led to a substantial



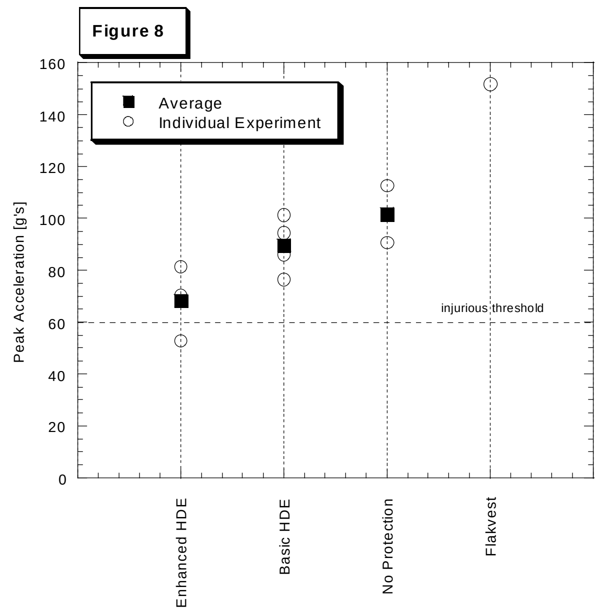


Figure 7. Peak overpressure measured at sternum of mannequins in kneeling-on-one-knee position, facing 200 gram C4 simulated mine, buried with 1 cm overburden, 0.66-0.68 m from sternum.

Figure 8. Average peak acceleration measured at chest of mannequins (same testing conditions as Fig. 7 apply).

reduction in the overpressure transmitted to the chest of the mannequin when compared to the unprotected case. The use of a flakvest, comprised entirely of layers of soft ballistic fabric, did not perform any better than wearing no protection, in as far as reducing the transmitted overpressure to the chest wall. In fact, it has been demonstrated that aprons or vests containing soft ballistics alone, can actually amplify the overpressure experienced at the chest, depending on the mine threat, separation distance, and the particular construction of the protective apparel. The HDE, which has a blast attenuation system comprised of rigid and soft ballistic materials, including an energy absorbing layer, effectively decouples the blast wave for the range of conditions tested and is able to reduce the transmitted overpressure to the thorax, thus reducing the possibility and extent of any injury. For a detailed study of the overpressure measurements for the entire range of blast AP mine threats considered and the implications in terms of injury potential, please refer to [1&4].

The peak resultant acceleration experienced by the mannequins when facing the 200 gram C4 simulated mine and dressed in the various protective gear is plotted in Fig. 8. It can be seen that the results for acceleration mirror those for overpressure, as the same trend in relative performance is observed. The Enhanced HDE is best able to attenuate blast induced accelerative loading to the chest cavity over the unprotected case, followed by the Basic HDE. On the other hand, the wearing of a flakvest, is capable of amplifying the measured chest acceleration. This effect is postulated to be a result of the soft ballistic material being accelerated and "slapped" on to the chest cavity. The construction of the HDE, which includes rigid and energy absorbing materials, is able to deflect the incoming blast more effectively and damp a portion of the resultant accelerative chest loading.

In order to provide a preliminary assessment of the potential for injury resulting from gross chest acceleration, the generally accepted threshold of 60 g's for accelerative chest injury, is superimposed on Fig. 8. As this value is derived from the automotive industry where the duration of the loading event is typically longer than that associated with the detonation of blast AP mines, the 60 g threshold can be viewed as somewhat conservative. Nevertheless, exceeding the threshold indicates a higher probability that chest acceleration injury will occur. It can be seen that for most of the data when the mannequin faces 200 gram of C4, the injurious threshold is exceeded. The acceleration experienced by the mannequin wearing a flakvest exceeds the injury threshold by approximately 150%! Although there are limitations in comparing the response of a Hybrid II chest subjected to blast loading against the injury threshold of 60 g's, the exercise provides a first approximation for the potential of injury posed to the deminer for the range of conditions tested and permits a relative assessment of the protective effectiveness of different ensembles.

5.0 Conclusions

A cross-section of equipment (helmets, aprons, vests, etc.) included as part of personal protective ensembles for demining were systematically tested under controlled but realistic conditions. Actual and simulated blast AP mines, in the range of explosive content between 50 and 200 g C4, were positioned at representative distances, i.e., 0.66-0.68 m, from the sternum of a prodding deminer, kneeling on one knee. Through the use of instrumented human surrogates, i.e., mannequins, it was possible to provide a quantitative evaluation of the effectiveness of the different equipment for the entire range of blast threats. It was necessary for MES to design special "blast resistant" positioning rigs, which permitted the surrogates, dressed in the different protective apparel, to be reproducibly positioned in the desired distance and configuration. An injury assessment was also made possible by relative comparisons of measurements of overpressure and blast induced acceleration at the head (or ear) and chest, with estimates of injury threshold, where available.

The benefits in personal safety gained by using a protective ensemble that is particularly designed for the application are quite evident. The stable helmet systems (HDH, Sport) which permit the integration of a full face (6.32 mm/0.25") visor, were most effective in reducing the overpressure experienced at the ear to levels where there was less than a 50% probability of an ear drum perforation for the entire range of blast conditions tested. These same helmets were similarly the most successful in reducing the blast induced head acceleration injury experienced to non-injurious, or survivable levels, even at the largest simulated AP mine blasts (200 gram C4). The HDH helmets, based on a PASGT-style helmet with a full face visor and a much improved retention system, proved to be the best performers overall against all mine blasts. Hardhat helmets with a full face visor were moderately effective in providing blast protection against the smallest mines (50 g C4), as was the case of a PASGT-style helmet with goggles and minimal facial protection. An increase in explosive content of the mine (100 and 200 gram C4) clearly escalated the injury severity that would be experienced by the wearer of a Hardhat; a very high likelihood of permanent hearing loss and a potentially unsurvivable head concussion could be anticipated. The open-faced PASGT-style helmet with goggles performed poorly against the larger mines compared to the helmets featuring a full-faced visor on a stable platform. In fact, the anticipated level of protection offered by the helmet without a visor against blast overpressure and head acceleration is comparable to not wearing any head protection and may sometimes actually escalate the injury potential. This can be attributed to the poor suitability of the design for the particular demining application and related blast threats.

The HDE demining ensembles (Basic and Enhanced) offered very significant reductions in transmitted overpressure to the chest wall and in gross chest accelerations, compared to the case of a flack vest or an unprotected mannequin. At the largest blast AP mine threat of 200 gram C4, it was apparent that the hybrid construction of the HDE's, involving soft and rigid ballistic materials with an energy absorbing layer, proved to be more suitable for the demining application compared to a flakvest. The flakvest offered a level of fragmentation resistance but did not contribute towards reducing blast induced chest acceleration and transmitted overpressure. The construction of a flakvest, comprised entirely of soft ballistic layers, was illustrated to actually amplify the loading that would be experienced by an unprotected mannequin.

This study was the first systematic attempt to elucidate the blast performance of personal protective ensembles for the specific purposes of demining. Equipment used must be considered in the context of the blast and fragmentation threats posed by the full range of blast AP mine threats. Protection provided against small mines or for one particular position/distance of the deminer, may be vastly compromised if the explosive content of the mine increases or the deminer comes into closer proximity to the mine. Studies are currently underway to quantify the effects of distance and position of the deminer relative to the AP mine and will be reported at a later occasion.

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